Recycling of Centers of Explosive Emission in a Cathode Spot of a Vacuum Arc

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Abstract – Non-stationary processes on a cathode and at a near cathode area of a vacuum arc are analyzed. Such processes can result in periodicity of occurrence of centers of explosive emission in a cathode spot.

1. Introduction

Nowadays the non-stationary cyclic model of processes in a cathode spot of a vacuum arc has found recognition among experts [1]. Rough allocation of energy with the rate of 10^{13}–10^{12} J/g s takes place during 10^{-9}–10^{-8} s in volumes on a surface of the cathode with the linear sizes 10^{-5}–10^{-4}cm. This process is accompanied by erosion of the cathode with the weight expiration rate of 10^{9}–10^{8}A/cm^2 in an electrical equivalent. The products of erosion turn into cathode plasma. The set of the described above phenomena has short-term character. As a result of erosion the linear sizes of a localization area of energy allocation are increased, the speed of allocation of energy falls, the process stops. According to the accepted terminology, the occurrence and functioning of the center of explosive emission or ecton took place [1]. For maintenance of conditions of existence of an arc the formation of the new repeated ecton is necessary and so on.

At present there is no settled opinion concerning mechanisms of delivery and concentration of energy on the cathode in quantity sufficient for the formation of the explosive emission center. These questions are discussed in the offered report.

2. Physical Model

The plasma is separated from the cathode by a layer of a spatial charge or with a cathode fall of potential layer w_c. The energy stored in plasma basically exists in an electronic component, with density nkT_e, n – concentration, k – Boltsman constant, T_e – electronic temperature. Plasma emits in the direction of the cathode a flow of electrons with density of current of $j_e \approx en(kT_e/2\pi m_e)^{1/2}\exp(-ew_c/kT_e)$, flow of ions with density of a current $j_i \approx en(kT_e/2\pi m_i)^{1/2}$, flow of radiation. Every plasma electron brings to the cathode energy – $w_{se} \approx ew_e + 2kT_e$, w_e – emission work function of the cathode.

The plasma ion brings to the cathode energy $w_{si} \approx ew_c + e(w_i - w_e) + w_{ev} + 3/2kT_i + kT_e$, w_i – potential of ionization of an ion, T_i – temperature of plasma ions, w_{ev} – energy of evaporation for one atom of the substance of the cathode. Second and fourth compose in the last formula are caused by charging neutralization of an ion on the cathode and by acceleration of an ion in plasma presheath (Bohm criterion). From the cathode there is an emission of electrons and heavy particles as neutral atoms and ions. Current density of emission of electrons j_{ee} from the cathode is described by complex formulas, depending on a ratio between electrical field intensity at the cathode and temperature of electrons in the cathode (field emission or E–T emission, thermionic, hot or T–E emission) [2]. At field emission leaves in the cathode energy $w_{\text{E–T}} \approx 2kT_{inv}$, T_{inv} – temperature of inversion (Nottingham effect), at thermoemission an electron carries away from the cathode energy $w_{\text{E–T}} \approx ew_e + 2kT_{ec}$, T_{ec} – temperature of electrons. The emission of heavy particles or rate of evaporation can be estimated under the formula $V_a \approx V_\perp \exp(-w_{ev}/kT)$, $V_\perp$ – transversal speed of a sound determined by energy of interaction and energy enclosed in the substance of the cathode. During evaporation each atom carries away from the cathode energy $w_a = ew_{ev} + 2kT$. In a layer between plasma and a cathode the electromagnetic fields caused by radiation from plasma by charges and by currents of particles, emitted from plasma and the cathode take place. Their role is determined by density of a flow of energy of a field (Umov-Pointing vector) $j_w = c/4\pi[\vec{E}\vec{H}]$, acting on the cathode. It is convenient to consider this vector as total, which includes energy of radiation coming from plasma, currents of electrons and ions introduced to the cathode and owing to Joule dissipation of substance, varying internal energy of the cathode. Also it is still convenient because the power supply of an arc has an electromagnetic nature, the energy is delivered to the cathode by a flow of energy of an electromagnetic field a layer thus plays a role of original waveguide. It is not necessary also to make the numerous assumptions concerning currents of electrons and ions. More or less plausible estimation of size of fields in the layer is sufficient. For amplitude of an electrical field the reasonable estimation is $E \le \sqrt{4\pi n kT_e}$. The magnetic field can be estimated proceeding from the equations of Maxwell.

Let's proceed from the equations of balance of particles and tensor of the energy – pulse that has been written down for allocated volume at a surface of the cathode

$$d(\int_V n_e dV)/d\,t = -\oiint_s \vec{j}\cdot d\,\vec{s}; \tag{1}$$

$$d(\int_V \vec{p} dV)/d\,t = -\oiint_s \hat{j}_p \cdot d\,\vec{s}; \tag{2}$$

$$d(\int_V w dV)/d\,t = -\oiint_s \vec{j}_w \cdot d\,\vec{s}; \tag{3}$$

n_e – total density of charge, j – total density of current, $\vec{p}$ – total density of a pulse of substance and field, $\hat{j}_p$ – total density tensor of a flow of a pulse, w – total density of energy, $\vec{j}_w$ – total density of a flow of energy. The obvious record of these sizes is possible at acceptance of concrete physical model. It is possible to consider three variants. The metal cathode, good vacuum conditions, pure surface of the cathode; bad vacuum conditions, dielectric films and pollutions are present on a surface of the metal cathode; micro sized particles fly from the cathode spot and they are responsible for repeated explosions. We shall stop on the first variant.

3. The Metallic Cathode, Pure Vacuum Conditions

The equations of a field (the Maxwell equations) take into account influence of substance through density of volumetric charge and density of current (without current of displacement). The substance of the cathode does not show properties of dispersion; relative dielectric and magnetic permeability are close to 1. The cathode spot is located at one place. The centers of explosive emission arise in immediate proximity from each other. A bath of liquid metal is formed at the place of the spot from which jets can throw out. Let's begin from consideration of balance of charge in a layer. It is possible to allocate two time scales. The first is time of flight of particles of the layer (of order of back plasma frequency). The second is change of parameters of the layer owing to change of conditions on the cathode. For the second case the equation (1) can be copied as

$$d(\int_L n_e dx)/dt = j_c - j_p, \tag{1a}$$

where L is thickness of the layer, j_c is density of current from the layer to the cathode, j_p is density of a current from plasma to the layer. Proceeding from the Poisson equation for a layer, it is possible to write

$$\begin{aligned} &\partial E/\partial\,x = 4\pi n_e; \\ &j_c = j_i + j_{ee} - j_e = 1/4\pi\cdot\partial E_c/\partial\,t. \end{aligned} \tag{4}$$

Let's write down right part of the Poisson equation as

$$n_e = Q_i - Q_{ee} - Q_{e1} - Q_{e2}; \tag{5}$$

$$\begin{aligned} &Q_i = en\sqrt{\pi}\exp(x_i)\cdot(1 - erf(\sqrt{x_i})), \\ &x_i = e_i(w_c - w)/kT_e + v_i; \end{aligned} \tag{6a}$$

$$\begin{aligned} &Q_{ee} = j_{ee}/(kT/2\pi m_e)^{1/2}\sqrt{\pi}\exp(x_{ee})\cdot \\ &(1 - erf(\sqrt{x_{ee}})),\quad x_{ee} = ew/kT + v_{ee}; \end{aligned} \tag{6b}$$

$$\begin{aligned} &Q_{e1} = en(1 - \exp(-ew_c/kT_e))\exp(-ew_c/kT_e - \gamma_e) \\ &\exp(x_e)erf(\sqrt{x_e}), \\ &Q_{e2} = en\exp(-ew_c/kT_e - \gamma_e)\sqrt{\pi}\exp(x_e) \\ &(1 - erf(\sqrt{x_e})),\quad x_e = ew/kT_e + v_e. \end{aligned} \tag{6c}$$

Here Q_i is volumetric charge appropriate to ions from plasma, Q_{ee} is volumetric charge of electron emission from the cathode, Q_{e1} is a volumetric charge of opposite electrons from plasma which do not reach the cathode and Q_{e2} is a charge of electrons from plasma reaching the cathode. The design (5) is chosen by us for the following reasons. It corresponds to functions of particles speed distribution in a layer satisfying to Vlasov equations, to boundary conditions for a layer from the side of the cathode and plasma and cold hydrodynamical limit

$$\begin{aligned} &Q_i = en(x_i)^{-1/2}, \\ &Q_{ee} = j_{ee}/(kT/2\pi\,m_e)^{1/2}(x_{ee})^{-1/2} \\ &Q_{e1} = en\,(1 - \exp(-ew_c/kT_e))\cdot \\ &\exp(-ew_c/kT_e - \gamma_e)\exp(x_e), \\ &Q_{e2} = en\exp(-ew_c/kT_e - \gamma_e\}(x_e)^{-1/2}. \end{aligned} \tag{7}$$

γ_a are parameters of effective polytropic exponents for components appropriate to movement in presheath [3]. The difference between (6) and (7) does not exceed 15%. As the right part of the Poisson equation depends only on potential, finding of the first integral is possible. It allows estimation of pondemotoric forces on the cathode, intensity of an electrical field, value of a current density j_c. Further let's estimate balance of energy on the cathode. Besides flows of energy determined above, the radiation from plasma and also brake radiation from opposite electrons can influence the cathode. The appropriate densities of flows of energy can be determined as follows

$$j_{ws} = s\,(T_e^4 - T^4); \tag{8}$$

$$\begin{aligned} &j_{wh} = n(kT_e/2\,\pi\,m_e)^{1/2}\cdot \\ &(1 - \exp(-ew_c/kT_e))2kT_e. \end{aligned} \tag{9}$$

The formula (8) assumes, that plasma contacting with the cathode is optically thick, s – Stefan-Boltzmann constant. The formula (9) is written down, proceeding from the following reasons. Plasma electrons are braked in a layer radiate and stop then come back to plasma moving with acceleration. Thus they absorb electromagnetic energy from an external source. If the layer was tangentially homogeneous, the trajectories of direct and return movement would be coincide, the total exchange of electromagnetic energy would be equal to zero. However plasma of a cathode flare torch is non-uniform. The layer reminds a wedge condenser or a diode. The force lines of an electrical field and trajectories of electrons are curves, ways of movement with deceleration and acceleration do not coincide. At movement with deceleration electron radiates, the part of energy of radiation can be absorbed by the cathode. At movement with acceleration electrons absorbs electromagnetic energy from the power supply unit. Thus, in our opinion, there is an electromagnetic feed of the arc discharge. Owing to the volume restrictions of the paper we shall not give detail comments on the form of the record (9). It is physically transparent and clear. In the further calculations we used within the limits of 10% from value given by (9). Let's also notice, that the formula (9) does not take into account brake radiation of electrons, reaching the cathode. In view of everything, stated above, the equation of warm balance on the cathode can be written down as

$$cdT/dt \approx (j_{wi} + j_{we} - j_{wee} - j_{wa})/a_1 + \\ + (j_{wh} + j_{ws})/a_2 + j^2 \cdot r. \qquad (10)$$

The first composed represents a particle source of energy including bombardment by ions and electrons from plasma cooling by electrons of emission and by evaporating atoms. The second composed corresponds to warming of the cathode by brake radiation from opposite electrons and by radiation from plasma. The third one is Joule warming up. Resulting density of current j changed in calculations from 0 up to j_c, and further up to the value of j_c. It did not render sufficient influence on results of calculations. Values a_1, a_2, r are length of heat diffusivity, skin length and specific resistance correspondently. As thermal and kinetic properties of material of the cathode are unknown for those values of temperatures, which calculations give, we extrapolated the help data, beginning from melting temperatures and above. The equation (10) is as though managing for all equations mentioned above. The change of temperature of the cathode entails change of electronic emission, corresponding alteration of density of current of plasma electrons to the cathode, change of cathode potential fall at a layer and all other parameters of a layer. Some results of calculations are given below.

4. Results of Accounts

Below as an example the results of calculations for copper are given. The analysis of hydrodynamic motion of plasma torch has shown that maximal density of energy in an electronic component corresponds to concentration $n \approx 10^{20}$ cm^{-3} and temperature of electrons $T_e \approx 5$ eV [2]. These values also are fixed in a basis of the calculation. The following values are chosen also: thermal capacity of unit of volume $c = 4$ J/cm^3 K; work of output $w_e = 4.4$ eV; energy of connection on atom $w_{ev} = 3.79$ eV; potential of ionization $w_i = 10$ eV; cross speed of sound $V_\perp = 10^5$ cm/s; parameters of polytropic exponents $\nu_i = 3$, $\nu_{ee} = \nu_e = 2$; the specific resistance was chosen as $r = (10^{-5} + 10^{-8}\,T)$ Ohm. The calculation began from melting temperature and came to end, when the fall of potential became close to zero. From Fig. 1 it is seen, that the warming up of the cathode occurs enough quickly, during time about millimicrosecond. Thus the fall of potential falls down from 35 volts up to 0. It matches well with experimental data [1]. From the first Fig. 2 it is seen, that density of current of emission from the cathode and density of a current from plasma actually coincide. Each of these parameters reaches the big value up to 10^9 A/cm^2. Resulting density of a current in this scale is very small. The Joule warming up also is small. It occurs because the flows electrons from the cathode and from plasma are evolution of density of flows of energy delivered to the cathode is shown. It is visible, that in the beginning the warming up of the cathode is defined by brake radiation opposite electrons from plasma. Then the bombardment of the cathode by plasma electrons becomes a primary factor. The analysis of density of pulses flows influencing the cathode, has shown the following. The biggest value is the force of feedback from evaporating atoms. Owing to volume limitation of the clause we do not bring in detail results of calculations.

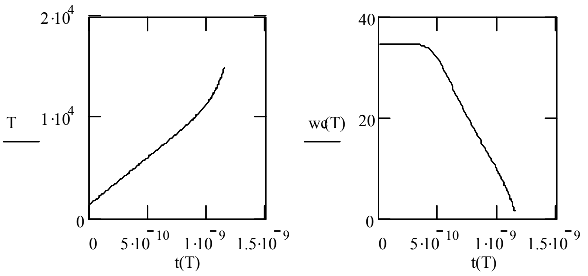

Fig. 1. Dependence of temperature of the cathode (K) and fall of potential (V) from time (s)

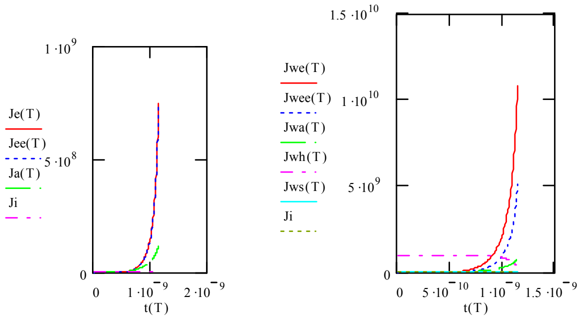

Fig. 2. Dependences of density of currents (A/cm^2) and density of flows energy (W/cm^2) on the cathode from time (s)

Let's note the most important things. The pressure reaches a value of 10^3 J/cm^3 and more. It corresponds to speed of movement of liquid metal $V \geq 10^4$ cm/s. The ledges on the cathode can derivate and drops with sizes of $d \approx 10^{-5}$–10^{-4} cm can fly. The given values have the quite good consent with the experiment.

These phenomena have accompanying character. For heating of the cathode it is not necessary to assume presence of a ledge with the large attitude of assembling surface to the minimal section, high factor of amplification on density of current, as it is offered in [1]. From the first Fig. 3 it is visible, that the intensity of an electrical field at the initial moment of time achieves very significant value. It strongly reduces work of an output, facilitates emission of electrons from the cathode and accelerates its warming up. In process of increase of emission of electrons both from the cathode, and from plasma the negative volumetric charge in a layer grows. The intensity of a field falls practically linearly in due course. Through electrical current with density j, spring up (see (4)). This value does not influence essentially the processes, as it is small in comparison with the emission from the cathode and from plasma. Some other thing is essential. As it is visible from the second Fig. 3, concentration of vapors of material of the cathode in a layer grows sharply. The layer becomes collisional on the phenomenon of recharge. The ions of plasma, colliding with atoms of the same grade,exchange with them by electrons and the described above model of a layer ceases to be fair. It is possible to use other representation. The ions are motionless, density of an electronic current from plasma achieves saturation and density of an electronic current from the cathode keeps growing. As both values are big, $\approx 10^9$ A/cm^2, the slightest difference between them results in sharp growth of through resulting current. Contraction of a current occurs. So it is possible to understand portion and origin of an electronic clot about what is said at definition of ecton [1]. The same offer can be added to vast discussion about the value of density of a current in a cathode spot. At contraction of a current with large density the cathode is exposed to strong local thermal impact by means of Joule dissipation. The phenomenon of explosive emission springs up, the intensive erosion of the cathode and transformation of products of erosion into plasma takes place. The size of the center of explosive emission is increased, density of a current falls and the process stops. One cycle is finished, the conditions for another one are prepared.

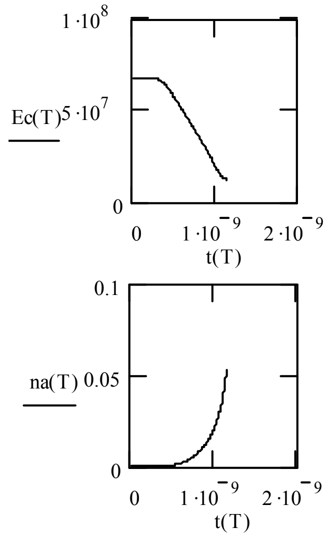

Fig. 3. Dependences on time of intensity of an electrical field (V/cm) on the cathode and concentration atoms (rather the condensed phase)

In the conclusion we shall note, that the representations about a conducting role of opposite electrons from plasma and about an electromagnetic way of delivery of energy to the cathode allow explaining in a natural way the phenomenon of back movement of a cathode spot in a tangential magnetic field. It was specified also in works [4].

References

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